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Parametrical experimental and numerical analysis on friction-induced vibrations by a simple frictional system

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ABSTRACT

This paper presents an experimental and numerical analysis on friction-induced vibrations arising from the frictional contact between two bodies in relative motion. The sliding contact has been reproduced within a mechanical system characterized by a simple dynamics, in order to better distinguish between the dynamic response of the system and the broadband excitation coming from the contact. The effects of some parameters, mainly relative velocity, roughness and normal load, on the magnitude and frequency content of the induced vibrations are investigated, also by comparing results from experimental measurements and simulations. A distinction between weak and strong coupling is recovered by the experimental results. Finally, accounting for the contribution of the roughness to the contact-induced vibrations, a conceptually innovative method to implement the effect of the roughness in the numerical simulation is proposed.

1. Introduction

Issues on Friction-Induced Vibrations (FIV) [1] have been and are still being intensively studied numerically [2–5] as well as experimentally [6–8]. The main reason behind this interest lies both in the wide field of interest that they cover and in the intriguing complexity of the phenomenon, which makes it still not fully understood. In fact, from one side, friction is present, and generally not completely suppressible, in most mechanical systems. On the other side the relevant number of variables affecting the contact and, by consequence the related induced vibrations, entails the impossibility of drawing an overall theory.

The basic mechanism characterizing the onset of the FIV can be schematized as follows: waves originate at the contact interface [9–12], then they propagate along the interface and into the bulk, being reflected when they reach the boundaries of the system. The interaction between the waves results in the excitation of the dynamics of the system. In the meantime, the waves come back to the contact interface too, affecting the contact conditions continuously. At least two different induced-vibration driving mechanisms can be distinguished, depending on the contact conditions:

- If the two bodies are in "weak" contact [13], waves are triggered by the impacts of the roughness asperities and propagate in each component exciting their own eigenfrequencies, nearly independently from each other. The induced vibrations usually come with sound generation, generally referred in this case as *roughness noise* to remark the primary cause, even if, obviously, the sound source is always related to the whole system. The *roughness noise* generally has low sound power and a frequency spectrum that, except the peaks related to the eigenfrequencies, has a broadband frequency range.
- In the case of "strong" contact conditions [13], the contact strength is able to modify the dynamics of the whole system, setting up a coupled dynamics of the components and the response is nonlinear [14]. In this situation, the friction forces can give rise to dynamic instabilities (sprag-slip, stick-slip, mode coupling [14–20]). Also in this case, there is sound generation but with a narrowband frequency spectrum, lumped on the system natural frequencies and their harmonics (or sub-harmonics).

Moreover, examining in depth the case of "strong" contact, different behaviours of the coupled system could be recognized, depending on the system parameters [21]: 1) Stable behaviour, characterized by continuous sliding with wideband and low amplitude vibrations in the transient response of the system; 2) Stick-slip instability with stick-slip macroscopic frictional behaviour; 3) Mode coupling instability, characterized by continuous sliding with harmonic self-excited friction-induced vibrations, due to an unstable mode (squeal); this latter condition being well explained by the modal lock-in [22].

The occurrence of a *weak* or *strong* contact conditions ultimately

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depends on the specific mechanical system, the applied boundary conditions and the contact interface features, e.g. the magnitude of the normal contact load and the friction coefficient.

In literature, works are mainly focused either on *weak* frictional contacts (i.e. roughness noise) [23–27] or on *strong* contacts and friction instabilities [3,4,7,28–31]. In this work, a system characterized by a simple dynamics and a simple contact interface has been used to span a large range of the boundary conditions, in order to investigate the system dynamic response under both weak and strong contact conditions. The simple dynamics of the system, together with the numerical analysis, allows for distinguishing between structural effects and contact effects on the amplitude and spectra of the induced vibrations.

In fact, either in the case of weak or strong contact conditions, the roughness affects the response of the system: in the former determining the sound and vibration magnitude and spectrum; in the latter influencing the dynamics of the coupled system, the frequency range of contact excitation and the onset and/or the magnitude of the instabilities. For instance, it has been observed that an elevation in surface roughness increases the strength of stick–slip motion, making it possible to develop even in the presence of large damping [32]. Moreover, in the case of modal coupling, even if the roughness is not necessary to the occurrence of instabilities, it has been observed that its presence promotes them [33]. Obviously, in weak contact conditions, roughness is one of the main factor that guides the system induced vibrations.

Consequently, by a numerical point of view, a desirable enhancement of a numerical model is to take into account the roughness and its effects on friction-induced vibrations. Different methodologies have been presented in literature to achieve this goal. They could be classified into four main groups depending on their own approach to the problem:

i) by modelling the surface trying to reproduce in some manner the asperities [26,32];
ii) by numerical implementation of algorithms that reproduce the impacts between the asperities [34,35];
iii) by modelling multi-contacts [36];
iv) by defining peculiar friction laws [37,38].

In this paper both experimental and numerical analyses are presented in order to discuss the role of each parameter (normal load, velocity, roughness etc.) in the friction-induced vibrations between two simple beams rubbed one against the other. The numerical and experimental results allow for identifying the mechanisms that play a main role in the different parameter ranges. In particular, the comparison with numerical simulations with smooth contact surfaces allows for decoupling the effect of roughness from the structural effects on the dynamic response of the system. Moreover, starting from the comparison with the experimental analysis, a numerical contact law is introduced into the numerical model to account for the effect of roughness. The used method could be qualified as belonging to the fourth group of the previous classification that is a definition of a specific friction law, but with a different conceptual approach. In fact, the fluctuations of the frictional force, related to the roughness, are treated as a stochastic term and implemented in the expression of the local friction coefficient.

First, the experimental and numerical reproduction of friction-induced vibrations, by the simple mechanical system presented in the first part of the paper, allows for highlighting the trend of FIVs as a function of some main parameters. Then, the last part of the paper proposes a different approach, with respect to ones present into the literature, to account for the roughness effects in the broadband contact excitation of a dynamic system. In the case of both “weak” and “strong” contacts, the proposed approach attempts to simulate the overall effect of the interaction between the contact surface topography (at the origin of the broadband contact excitation) and the system dynamic response, by the introduction of a perturbative term in the contact algorithm, without simulating an accurate reconstruction of the roughness surface (i.e. without increasing the dimension of the numerical model). This approach, if validated, could represent an easier and flexible way to quickly implement the dynamic roughness effect on a numerical model.

The paper is organized as follows: in Section 2, the experimental setup is presented and the results of the measurements in function of different parameters are described. In section 3 the numerical model is introduced and the different analyses performed on the model, linear modal analysis and non-linear transient simulations, are presented. In section 4, a systematic comparison between the experimental and numerical results is performed to investigate the main phenomena occurring at the variation of the boundary conditions. Finally, in section 5, an implementation of a friction law accounting for the roughness, is proposed to retrieve the experimental amplitude of the friction-induced vibration spectra.

2. Experimental analysis

The experimental analysis has the aim of investigating the dynamic response of two beams in contact, sliding under external imposed conditions. The experimental set-up (Fig. 1) gives the possibility of imposing the horizontal velocity of the lower beam as well as the vertical displacement (load) of the upper beam and the angle of inclination of the upper beam. Furthermore, the roughness of the

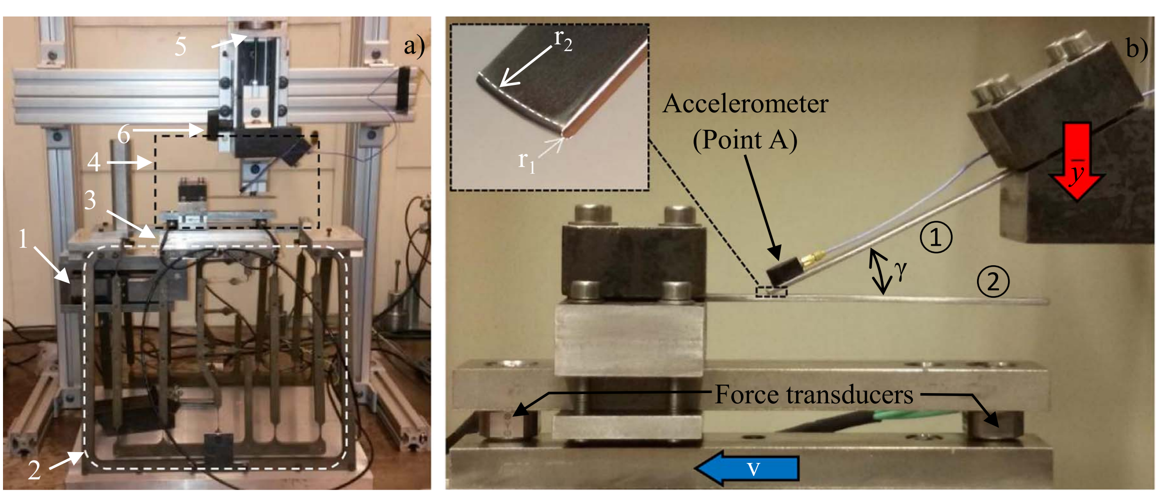

Fig. 1. a) Experimental setup: 1 Linear voice coil, 2 Compliant device, 3 Upper base, 4 Beams arrangement, 5 Screw guide mechanism, 6 screw knob; b) Zoom of beams fastening device.